Detection of Diffuse Interstellar Bands in the $z = 0.5$ Damped Lyman α system towards AO 0235+164[1]

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ABSTRACT

We report the first detection of the 5705 and 5780 Å Diffuse Interstellar Bands (DIBs) in a moderate redshift Damped Lyman-α (DLA) system. We measure a

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rest frame equivalent width of 63.2 ± 8.7 mÅ for the 5705 and 216 ± 9 mÅ for the 5780 Å feature in the $z_{\rm abs} = 0.524$ DLA towards AO 0235+164 and derive limits for the equivalent widths of the bands at 5797, 6284, and 6613 Å. The equivalent width of the 5780 band is lower than would be expected based on the Galactic correlation of DIB strength with N(H I), but is in good agreement with the correlation with E(B−V). The relative strengths of the 5780 and 6284 Å DIBs are inconsistent with all Galactic and extragalactic sightlines, except one Small Magellanic Cloud wing sightline towards Sk 143. However, the relative strengths of the 5705 and 5780 Å DIBs *are* consistent with the Galactic relation, indicating that the relative strengths of these bands may be less sensitive to environment or that they may be associated with a similar carrier. The detection of DIBs at $z \sim 0.5$ demonstrates that the organic compounds usually assumed to be the band carriers were already present in the universe some five gigayears ago.

Subject headings: QSOs: absorption lines — QSOs: individual AO 0235+164 — ISM: molecules — ISM: lines and bands

1. INTRODUCTION

The diffuse interstellar bands (DIBs) are a series of broad absorption lines found between 4000 and 13000 Å. First detected more than 80 years ago (e.g. Merrill 1934), there are now several hundred known diffuse bands (e.g. Cox et al. 2005). The molecular origin (carrier) of the DIBs remains a mystery. Amongst the potential candidates are polycyclic organic hydrocarbons (PAHs), fullerenes, and long carbon chains (Herbig 1993).

In addition to DIB detections towards hundreds of stars in the Milky Way (see Herbig 1995 for a review), the DIBs have also been detected in the Large and Small Magellanic Clouds (LMC, SMC e.g. Cox et al. 2005; Ehrenfreund et al. 2002; Welty et al 2006), in NGC 1448 (Sollerman et al. 2005), and in several starburst galaxies (Heckman & Lehnert 2000). Recently, the 4428 Å DIB was detected in a Damped Lyman-α system (a high column density H I absorber with N(H I) $\geq 2.0\times 10^{20}$ cm^{-2}, here N(H I) $= 5.0\times10^{21}$cm^{-2}) with $z_{\rm abs} = 0.524$ (DLA) towards the $z = 0.94$ QSO AO 0235+164 by Junkkarinen et al. (2004), the first detection of a DIB at cosmological distances.

[1]Based on observations made with ESO Telescopes at the Paranal Observatories under programme ID 075.C-0029

Given the Galactic correlation between N(H I) and DIB strength (Herbig 1993), high N(H I) DLAs represent a promising site for DIB detection beyond the local universe. Since DIB strength appears to be sensitive to local conditions in the interstellar medium (ISM) such as dust-to-gas ratio and UV radiation field (e.g. Welty et al 2006), measurements in DLAs may provide clues into the ambient environment of high redshift galaxies. The detection of DIBs in DLAs also offers the potential to test relationships which have been observed locally, such as the various 'families' of DIBs whose strengths show tight correlations (e.g. Moutou et al. 1999) and may be linked to the same carrier. Observing identical correlations in galaxies with different conditions (such as metallicity and radiation field) is a critical test for the family hypothesis. We have therefore embarked upon a survey for the 5780 Å and other strong DIBs in moderate redshift DLAs. The full sample of six absorbers will be presented in Lawton et al. (in preparation); here we present a detections of the 5705 and 5780 Å feature towards one of our program QSOs, AO 0235+164. There is a well-known, high N(H I) DLA in this sightline at $z_{\rm abs} = 0.524$ (e.g. Junkkarinen et al. 2004). This absorber is unusual in several respects: it has a low spin temperature (Kanekar & Chengalur 2003), a relatively high metallicity and reddening, and exhibits both the 2175 Å dust feature and the broad 4428 Å DIB (Junkkarinen et al. 2004).

2. OBSERVATIONS AND DIB DETECTION

We obtained six 1400-second longslit spectra of QSO AO 0235+164 using the FORS2 spectrograph at the VLT. We used the 600z grism and a 1.0 arcsecond slit which yielded spectral coverage between 7370 and 10700 Å, and a FWHM resolution of 5.41 Å ($\sim$ 3.3 pixels). At a redshift of 0.524, the spectral coverage of the 600z grism was sufficient to search for the 5705, 5780, 5797, 6284, and 6613 Å DIBs. The final S/N ratio ranged from $\sim$ 60 (in the far red, which is badly affected by night sky lines) up to $\sim$ 150 per pixel. The 4428 Å DIB, previously detected by Junkkarinen et al. (2004), was not covered by our data.

The data were reduced using standard procedures and IRAF routines as described in Lawton et al. (in preparation). Neither the 5705 nor the 5780 Å DIB are directly contaminated by strong sky lines within three resolution elements. In Table 1 we give the measured rest frame equivalent widths (EWs) or 5 σ upper limits (where we paid special attention to the impact of night sky lines, see Lawton et al., in preparation) for the strong DIBs covered by our data. In addition, Na I $\lambda\lambda$ 5889, 5895 was detected with rest frame EWs = 793, 997 mÅ respectively.

3. DISCUSSION

3.1. The 5780 Å DIB Strength

Herbig (1993) has shown that, in the Milky Way, a strong relationship exists between the EW of the 5780 Å DIB and the H I column density of the line of sight. This relationship has been confirmed and improved using a much larger and more accurate Galactic database (D. York, private communication). In Figure 2, we show the 5780 EW of Galactic sightlines, based on data from Herbig (1993) and the fit to a more extensive dataset from Welty et al (2006) which includes sightlines with N(H I) $\lesssim$ 21.6. We also show extragalactic sightlines (see the larger online version of Table 1) and the 5780 detection towards AO 0235+164. Even though the scatter in the 5780–N(H I) relationship is considerable, the 5780 EW measured towards AO 0235+164 is lower than Galactic best fit line by six times the RMS scatter. It is possible that this relationship scales with metallicity, which for the DLA towards AO 0235+164 may be subsolar: $Z = (0.72 \ \pm \ 0.28)Z_{\odot}$ (Junkkarinen et al. 2004) as measured from X-ray data. An elemental abundance for the DLA based on UV resonance lines such as Fe II or Zn II would provide an important check of the X-ray metallicity. Welty et al. (2006) have compiled the most complete list of DIB measurements in the LMC ($Z = 0.4Z_{\odot}$) and SMC ($Z = 0.2Z_{\odot}$), including sightlines with N(H I) $\lesssim 10^{22}$ cm^{-2}, and find that the 5780 DIB is typically a factor of eight (LMC) and 20 (SMC) times weaker than in Galactic sightlines of the same N(H I). These deficiencies cannot be compensated for by a linear metallicity scaling. Although the abundances of metals (as raw materials for the DIB carriers) may have some impact on H I scaling relations, it is likely that other factors also play a role in the relations and their breadth, as discussed in the next subsection.

Interestingly, although the LMC and SMC points have low 5780 EWs for their N(H I) compared to the Galactic relation, Welty et al. (2006) show that the MC sightlines are in much better agreement with the Galactic scaling relation with E(B−V). We reproduce this relationship in Figure 2 and include the value of E(B−V)=0.23 for the DLA towards AO 0235+164 derived by Junkkarinen et al. (2004). As for the MC sightlines, the DLA also lies close to the Galactic points on this graph. We remind the reader that N(H I) is a measure of the gas phase, while E(B−V) measures dust.

3.2. Relative DIB Strengths

Some of the DIBs are found to correlate well with one another, and these sets are known as 'families' which may occur in the same carrier (e.g. Moutou et al. 1999). However, Wszolek & Godlowski (2003) note that correlation alone does not suggest that the members

of the family arise from the same carrier, suggesting that correlated DIBs might instead arise from different carriers which tend to occur in the same environments. Those families which are thought to arise from the same carrier are known as 'spectroscopic families', and generally include only one strong DIB. In particular, all of the other DIBs associated with the 5780 Å DIB by Wszolek & Godlowski (2003) (such as the features at 5776 and 5795) are weak DIBs, with typical Galactic EWs $\lesssim$ 20 mÅ, considerably below our detection limits. Although we can not test the spectroscopic families with the current data, the relative strengths implied by the detection limits of the other strong DIBs covered by our spectrum have implications for the environment of the DLA towards AO 0235+164.

Cami et al. (1997) divide the sight-lines along which DIBs are found into four groups: ζ, σ, Orion, and circum-stellar which they argue may be understood in terms of the strength of the local UV field. In particular, Cami et al. (1997) find evidence that the ionization potential of the 5797 Å DIB is lower than that of the 5780 Å DIB, which allows them to place the cloud types on a continuum, with the ζ-type cloud having a low UV field, and roughly equal strengths of the 5780 and 5797 Å DIBs, while the σ-type cloud has a sufficiently high UV field that the 5797 Å DIB has started to weaken, while the strength of the 5780 Å DIB is still increasing. They hypothesize that the Orion-type cloud represents an environment with a very high UV background, where even the carrier of the 5780 Å DIB has started to be destroyed. The σ/ζ dichotomy is thus the difference between the cloud outer skin and the inner flesh of the cloud, with self-shielding in the skin (σ-type) dramatically reducing the UV field inside the cloud (ζ-type). Unfortunately, our limit on the EW of the 5797 Å feature is not deep enough to distinguish between σ- and ζ-types, partly because of the proximity of this feature to a night sky line. High-resolution spectroscopy might be able to distinguish the 5797 Å DIB, if present, and give a better chance of measuring the relative ratios. This is technically feasible if the QSO is observed during its bright phases when its magnitude may reach $R \sim 15$.

Despite the lack of a deep 5797 Å EW limit, it is clear that the relative DIB ratios in the DLA (see Table 1 and Figure 3) do not match any of the Galactic sightlines, due to the low upper limit on the 6284 Å DIB. The only sightline known to show a similarly weak 6284 Å feature is Sk 143, a sightline in the SMC. Ehrenfreund et al. (2002) note that this sightline is located in the SMC wing, which is likely more protected against UV radiation than the rest of the SMC, and is very unusual in that it exhibits traces of the 2175 Å dust bump. The DLA towards AO 0235+164 also shows the 2175 Å dust bump (Junkkarinen et al. 2004), a rarity (although not unknown) in QSO absorbers (Wang et al. 2004; York et al. 2006). There has been considerable debate over whether DIB strengths correlate with bump strength, with claims both for and against (e.g. Herbig 1993; Désert, Jenniskens & Dennefeld 1995). It is clear, however, that any correlation has a large scatter and the

presence of the 2175 Å bump in both Sk 143 and AO 0235+164 may be a red herring. For example, strong DIBs have been found in starburst galaxies where the 2175 Å feature is definitely absent (Heckman & Lehnert 2000).

One interesting correlation that we can probe directly is the correlation between the 5705 and the 5780 Å DIBs presented in Thorburn et al. (2003). In this case, the 5705 EW is within 10 mÅ of that predicted by the Galactic relationship of Thorburn et al. (2003), consistent with our 1σ EW error plus the (small) scatter in the 5705–5780 relation. This strongly suggests that these two DIBs either react similarly to changes in environment or that they have closely related carriers.

The correlation of 5780 Å EW with E(B−V) and N(H I) indicates that, in the future, the best targets for extragalactic DIB surveys are those towards reddened, rather than simply the high column density, sightlines. The better correlation of 5780 with E(B−V) may be because the reddening combines both information on metallicity and the UV radiation. Most DLAs have very low values of E(B−V) (Murphy & Liske 2004; Ellison, Hall & Lira 2005), although Wild, Hewett & Pettini (2006) have recently identified a class of absorbers detected via Ca II absorption which have more significant reddening. However, the composite of the strongest Ca II absorbers was best fit with an E(B−V) $\sim$ 0.1, which (following the relation between reddening and 5780 EW) would still only yield a DIB with an equivalent width of $\sim$ 13–80 mÅ. It is therefore likely that DIBs in QSO absorption systems will only be observed in rare cases where the reddening is high (Lawton et al., in preparation).

4. SUMMARY

We have detected the 5705 and 5780 Å DIBs in a DLA at $z_{\rm abs} = 0.524$ in a DLA towards AO 0235+164, and determined upper limits for the 5797, 6284, and 6613 Å features. The EW of the 5780 Å feature is lower for its N(H I) than predicted by extrapolating the relationship in Herbig (1993), indicating that the relationship may depend on metallicity and/or the local radiation field. In contrast, the 5780 EW is in good agreement with Galactic sightlines for its E(B−V), as has also been observed towards Magellanic Cloud sightlines.

Unusually, the 6284 Å DIB has an upper limit which is lower than the EW of the 5780 Å feature, a situation which is not generally found in the Milky Way, or extragalactic sightlines. The one documented case of a similarly weak 6284-to-5780 ratio is towards the SMC wing sightline Sk 143. That sightline has other characteristics in common with the DLA, including the presence of the 2175 Å bump in the extinction curve, and a higher metallicity than is typical for the SMC, possibly because of a lower radiation field. On the other hand, the ratio

of 5705-to-5780 DIBs is in close agreement with the Galactic relation. This may be because these DIBs respond similarly to changes in environment (e.g. they have similar ionization potentials) and/or they have similar carriers.

Observations of H_2 in this DLA would be particularly interesting. The relative populations of various rotational levels would allow us to determine the kinetic temperature of the gas, its density and incident flux. This goal is not possible with current instrumentation, since the Lyman and Werner bands are in the far-UV at $z \sim 0.5$. However, the Cosmic Origins Spectrograph (COS), scheduled to be installed during the next *Hubble Space Telescope* servicing mission, would be able to detect H_2 in ~ 15 orbits (depending on the molecular fraction and the brightness of the QSO at the time of observation), whilst simultaneously providing a metallicity based on UV resonance lines. Although future detections of DIBs towards QSO absorption lines are likely to be challenging, due to the low incidence of highly reddened sightlines, probing high redshifts allows us to determine the epoch at which these organic compounds could form in the ISM. The detection of DIBs at $z \sim 0.5$ shows that these particular carriers were already present some five billion years ago.

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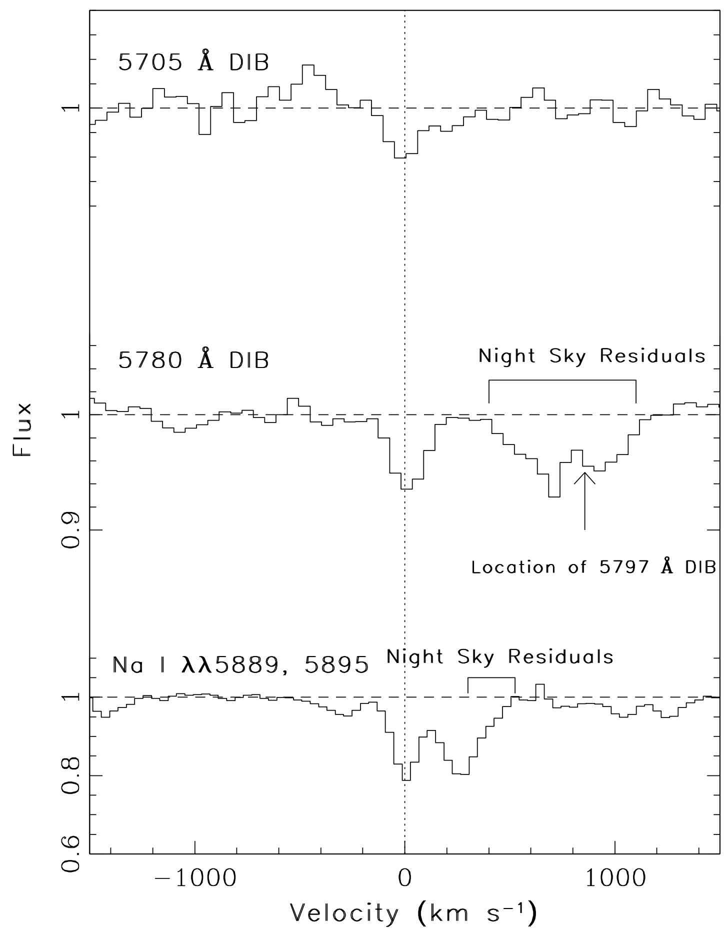
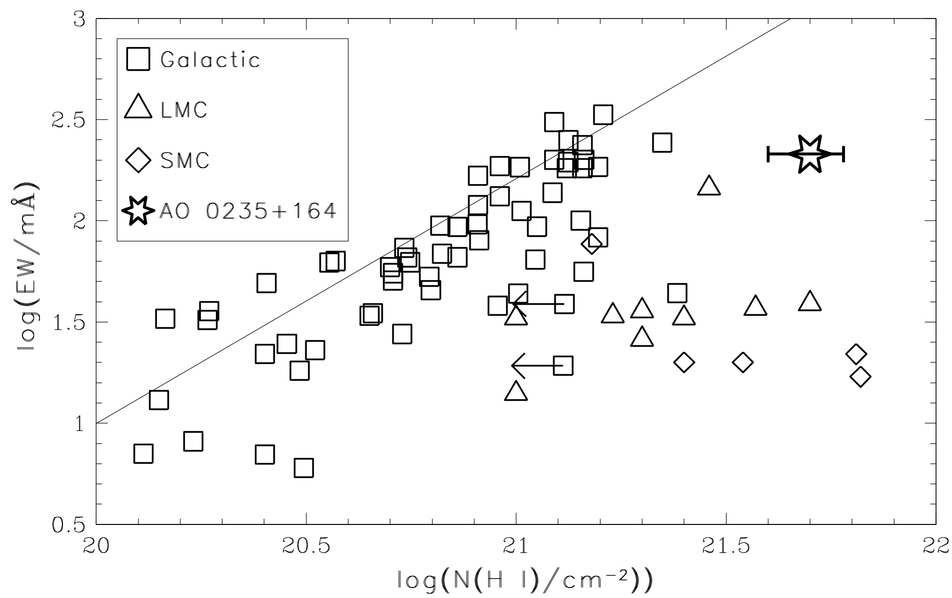


Fig. 1.— Detection of the 5705 Å DIB (upper spectrum), 5780 (middle spectrum, with the location at which the 5797 feature would be located marked) and Na I doublet (lower spectrum, centred on the Na I λ 5889 component) in the DLA towards AO 0235+164. The velocity scale is relative to $z_{\rm abs} = 0.5238$, which provides the best zero point for Na I λ 5889. The limit for the 5797 Å DIB is based on simulations taking into account the effects of contamination from sky lines.



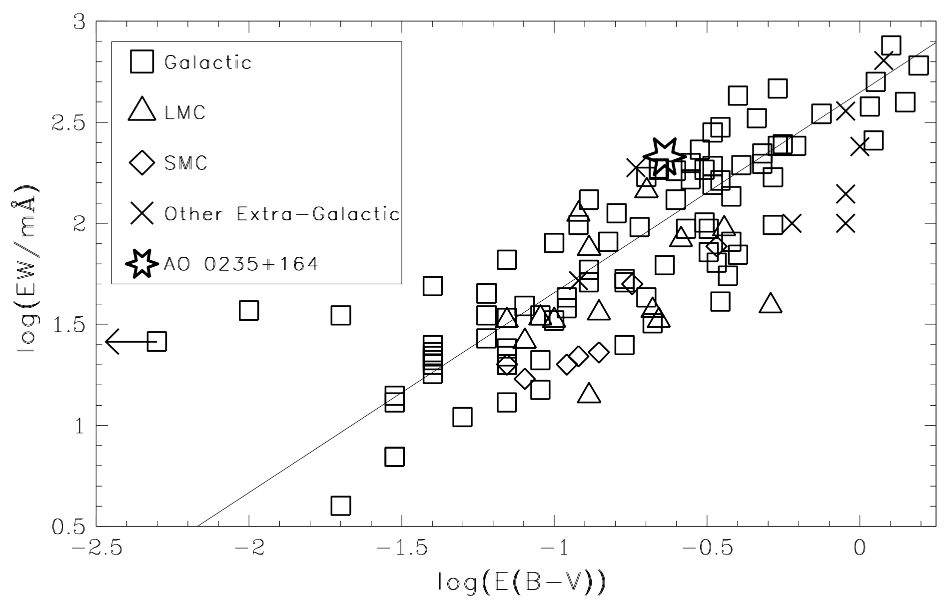


Fig. 2.— The 5780 – N(H I) and the 5780 – E(B−V) relationships. Galactic points from Herbig (1993), and extragalactic points as listed in Table 1 (and additional material online). Horizontal error bars are for a 1σ error, while vertical error bars are smaller than our point size. Best fit lines for the Galactic data are from Welty et al. (2006).

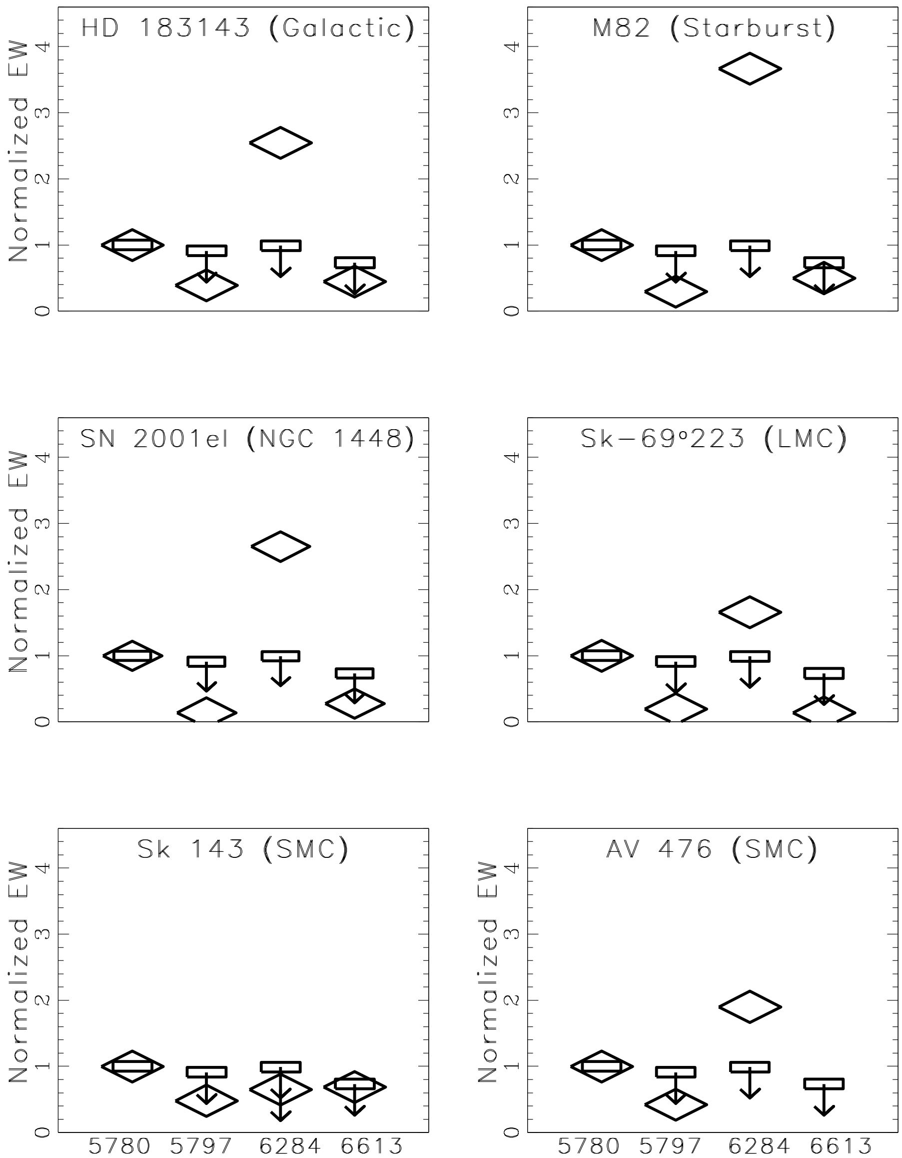


Fig. 3.— Relative equivalent widths of the diffuse interstellar bands, normalized to the equivalent width of the 5780 Å DIB (see Table 1 for EWs). In each case, the rectangles represent our data, while the diamonds represent the comparison sightline.

Table 1. Relative Equivalent Widths of various Diffuse Interstellar Bands

Source	Location	log(N(H I)) log(cm^{-2})	E(B−V)	5705 Å (mÅ)	5780 Å (mÅ)	5797 Å (mÅ)	6284 Å (mÅ)	6613 Å (mÅ)
AO 0235+164	DLA	$21.70^{+0.08}_{-0.10}$ (1)	0.23 (1)	63.2 ± 8.7	216 ± 9	< 197	< 214	< 158
Sk−69°223 (2)	LMC	21.46	0.2	···	145 ± 2	28 ± 6	240 ± 21	20 ± 8
Sk 143 (3)	SMC	21.18	0.34	···	77 ± 10	37 ± 4	< 50	53 ± 4
AV 476 (3)	SMC	···	0.18	···	50 ± 11	21 ± 5	95 ± 25	···
SNe 2001el (4)	NGC 1448	···	0.185	···	189	26	500	52
M82 (5)	Starburst	···	1.0	···	240	70	880 ± 30	120
HD 183143 (6)	Galactic	21.54	1.27	172 ± 7	758 ± 8	295 ± 10	1930 ± 150	337 ± 4

References. — (1) Junkkarinen et al. (2004); (2) Cox et al. (2006); (3) Welty et al. (2006); (4) Sollerman et al. (2005); (5) Heckman and Lehnert (2000) (6) Thorburn et al. (2003).

Note. — All quoted limits are 5 σ and error bars are 1 σ. A full list of extragalactic values used in Figure 2 is given in the online version of this table.